Numerical Investigation on the Reynolds Number Effects of Supercritical Airfoil

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Abstract

Supercritical airfoil has been widely applied to large aircrafts for sake of high aerodynamic efficiency. The aerodynamic characteristics of supercritical airfoil are rather sensitive to Reynolds number. Therefore, Reynolds number has great effects on the economy, comfort and even safety of large aircrafts. Flows over a typical supercritical airfoil XY are numerically investigated for different Reynolds numbers in this paper; the two-dimensional Navier-Stokes equations are solved with structure grids by utilizing the Spalart-Allmaras (S-A) turbulence model. Computational results of RAE2822 airfoil compare well with wind tunnel results. The computation Reynolds numbers of XY airfoil vary from $2.0 \times 10^6$ to $50 \times 10^6$ per airfoil chord while mach numbers equal 0.74 and 0.8. It is shown that the upper surface pressure distribution including the location and intensity of shock wave and trailing-edge pressure coefficient, changed apparently with variable Reynolds numbers, when shock-induced trailing-edge separation exists. Results implied that Reynolds number effects should be considered while designing and optimizing large aircrafts applied supercritical airfoil.

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Keywords: supercritical airfoil; Reynolds number; numerical simulation.

1. Introduction

Reynolds number representing the inertia force to viscous force is one of the most important similarity parameters in wind tunnel test. Supercritical airfoil has been widely applied to large aircrafts for sake of high aerodynamic efficiency. The aerodynamic characteristics of supercritical airfoil are rather sensitive to
Reynolds number at cruise conditions. The apparent difference of Reynolds number will cause the accumulated discrepancy of boundary layer equaling the change of wing geometry, which will result in different pressure coefficient distribution and affect the lift, drag and pitching moment coefficient [1]. Therefore, Reynolds number has great effects on the economy, comfort and even safety of large aircrafts. An air accident of C-141 airplane nearly occurred during flight test for terrible prediction of lift and pitching moment acting on the wing, which results from different shock wave location brought by Reynolds number effects. However, the Reynolds number of large aircraft at flight condition cannot be simulated in normal wind tunnel except cryogenic wind tunnel such as ETW or NTF at high cost. As a supplementary method, the expenditure of numerical simulation is very low to predict the Reynolds effects of large aircraft or supercritical airfoil[2].

Flows over a typical supercritical airfoil XY are numerically investigated for different Reynolds numbers in this paper; the two-dimensional Navier-Stokes equations are solved with structure grids by utilizing the Spalart-Allmaras (S-A) turbulence model. The computation Reynolds numbers of XY airfoil vary from $2.0 \times 10^6$ to $50 \times 10^6$ per airfoil chord while mach numbers equal 0.74 and 0.8.

2. Numerical Method

2.1. Governing equations

2D non-dimensional Navier-Stokes equations [3]:

$$\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = 0$$

(1)

Where

$$Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ E \end{pmatrix} \quad F = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (E + p)u \end{pmatrix} \quad G = \begin{pmatrix} \rho u \\ \rho uv \\ \rho v^2 + p \\ (E + p)v \end{pmatrix} \quad G_v = \frac{1}{Re} \begin{pmatrix} 0 \\ \tau_{yx} \\ \tau_{yy} \end{pmatrix}$$

$$\tau = \begin{pmatrix} (2\mu + \lambda)u_x + \lambda v_y \\ (2\mu + \lambda)v_y + \lambda u_x \\ (2\mu + \lambda)v_y + \lambda u_x \end{pmatrix}$$

$$\tau_{yx} = \frac{\mu}{(\gamma - 1)M_o^2 \Pr} \quad \tau_{yy} = \frac{\mu}{(\gamma - 1)M_o^2 \Pr}$$

$$q_x = -\frac{\mu}{(\gamma - 1)M_o^2 \Pr} \quad q_y = -\frac{\mu}{(\gamma - 1)M_o^2 \Pr}$$

Where the variables with subscript ‘I’ represent the inviscid counterparts and variables with subscript ‘V’ are the viscous counterparts.

The viscous coefficient is given by Sutherland’s equation:

$$\frac{\mu}{\mu_0} = \left( \frac{T}{273.16} \right)^{1.5} \frac{T + 110.4}{T + 110.4}$$

(2)
Where the variable \( \mu_0 \) is the air viscous coefficient when temperature is 273.16K and atmospheric pressure is \( 1.013\times10^5 \) Pa.

2.2. Governing equations solution method

Spalart-Allmaras turbulence model has been mainly applied in this paper while \( \kappa-\omega\)-SST(SST) turbulence model was only for test case computation in comparison with Spalart-Allmaras turbulence model. The spatial discretization is ROE scheme and time march applies LU-SGS [3]. Far field and wall boundary conditions have been applied to solve the governing equations in this paper.

2.3. Computing model and grid

Flows over a typical supercritical airfoil XY are numerically investigated in this paper. As shown in Fig.1, the upper surface of airfoil XY is rather flat which delays the occurrence of shock wave, and the lower surface has an aft-loaded camber compensating the loss of lift with the 250mm airfoil chord. It is shown in Fig.2 that structured grids have been applied. The computational grids have been generated by commercial software with a grid number about 120,000. The grid distribution on wall surface meets \( y^+ = 1 \). Airfoil RAE2822 for case study has the similar grid distribution.

![Fig. 1. Sketch of XY supercritical airfoil.](image1)

![Fig. 2. (a) Overview of computational grids; (b) Distribution of grids near the XY airfoil wall.](image2)

3. Results and Discussion
3.1. Case study

Flows over airfoil RAE2822 have been numerically solved with two different turbulence model, aimed to choose a better turbulence model, also to verify the codes applied in this paper reliable in comparison with wind tunnel results. Numerical simulation has been finished under the condition that \( M=0.74, \alpha=4^\circ \) and \( Re=6.5\times10^6 \). Pressure coefficient distribution of RAE2822 shown in Fig.1 was obtained by numerical simulation with S-A turbulence model. Comparison of computational results and experimental results has been finished. As shown in Fig.1, computational results obtained by S-A turbulence model compare better with experimental results than those obtained by SST turbulence model, especially on capturing the shock wave location. Therefore, S-A turbulence model has been applied in this paper.

3.2. Computational conditions

The computation Reynolds numbers of XY airfoil vary from \( 2.0\times10^6 \) to \( 50\times10^6 \) per airfoil chord and angles of attack from \( 4^\circ \) to \( 8^\circ \) in this research when mach numbers equal 0.74 and 0.8. Only typical results have presented in this paper.

3.3. Results and discussion

Fig.4 to 5 have shown typical results of Reynolds number effects on pressure distribution of XY airfoil, the training-edge pressure coefficient and pressure gradient along wall direction which suggests shock wave location and intensity. It can be seen that the upper surface pressure distribution including the location and intensity of shock wave and trailing-edge pressure coefficient, changed apparently with variable Reynolds numbers, while the lower surface pressure distribution is not so sensitive to the Reynolds number. As the Reynolds number increases, the boundary layer of upper surface gets thinner, the location of shock wave moves afterward, intensity of shock wave increases, trailing-edge pressure coefficient improves. It is not difficult to infer that increasing Reynolds number will improve the lift and drag characteristics in a whole, also a nose down pitching moment will occur [4].
Curves describing the relationship of training-edge pressure coefficient and Reynolds number in Fig. 5 are parallel, which implies that there is some potential relationship between training-edge pressure coefficient and Reynolds number. The high Reynolds number training-edge pressure coefficient may be extrapolated from low Reynolds number training-edge pressure coefficient based on this relationship.

It is also evident that the Reynolds number effects are much more serious when Re<20×10^6 than those when Re>20×10^6. Unfortunately, the Reynolds number of experimental data obtained from ordinary wind tunnel for large aircraft is usually about 4 million while the flight Reynolds number above 30 million. It is should be noticed that the low Reynolds number wind tunnel data be corrected before utilizing it to the design of large aircraft.

Fig. 4. (a)Reynolds number effects on pressure distribution of XY airfoil at α=4°, M=0.74; (b)Reynolds number effects on pressure distribution of XY airfoil at α=4°, M=0.8.

Fig. 5 (a)Reynolds number effects on training-edge pressure coefficient of XY airfoil at M=0.74; (b)Reynolds number effects on pressure gradient along wall direction at α=4°, M=0.74.
Fig. 6. (a) Reynolds number effects on the flow field around XY when Re=5×10^6; (b) Reynolds number effects on the flow field around XY when Re=40×10^6; both under conditions of α=6°, M=0.8.

Furthermore, typical results of the Reynolds effects on the flow field around XY airfoil have been presented in Fig.6. It is also shown that the shock wave location moves afterward and the intensity of shock wave increases with Reynolds number increasing. As shock wave intensity strengthens, the energy loss after shock wave increases, resulting in the mechanical energy loss of shock induced training-edge separated flow, thus improving the pressure recovery characteristics after shock wave.

4. Conclusion

It is concluded that the upper surface pressure distribution changed apparently with variable Reynolds numbers, when shock-induced trailing-edge separation exists. As the Reynolds number increases, the location of shock wave moves afterward, intensity of shock wave increases, trailing-edge recovery pressure coefficient improves. Results implied that Reynolds number effects should be considered while designing and optimizing large aircrafts applied supercritical airfoil. It is possibly credible to extrapolate the low Reynolds number wind tunnel data to flight data through relations of the shock wave location, pressure recovery characteristics and Reynolds number obtained from numerical simulation.

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